Development of a polarimeter for magnetic field measurements in the ultraviolet

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ABSTRACT

The polarizing optics that are being developed for the Solar Ultraviolet Magnetograph Investigation (SUMI) are described. This polarimeter is being designed for a sounding rocket payload which will make simultaneous measurements of two magnetically sensitive lines CIV (1550 Å) and MgII (2800 Å). With a limited observing program, the polarizing optics will be optimized for circular (V) and linear (Q) polarization measurements in active regions. The Q polarization will represent exploratory measurements of the transverse field in strong sunspots. This paper will give a brief overview of the SUMI instrument and its scientific goals, will describe the polarimeter that will be used in the sounding rocket program, and will present some of the measurements that have been made on the SUMI polarization optics.

1. INTRODUCTION

A major focus of solar physics is the measurement of the temporal and spatial variability of solar magnetic fields from the photosphere into the lower corona, and determining how this variability produces the dynamic phenomena in this region of the solar atmosphere. Some success has been achieved in the characterization of the full vector field in the photosphere, where β, the ratio of the gas pressure to the magnetic pressure, is ≥ 1. But at higher levels in the atmosphere[4] where $\beta \ll 1$, the magnetic field (through the Lorentz force) controls the structure and dynamics of the solar atmosphere, and rapid changes in its structure can produce energetic events. However, observations of the magnetic field at these higher levels have proven to be extremely difficult, placing a serious limitation on our understanding of the physical processes actually occurring there. This paper will discuss the Solar Ultraviolet Magnetograph Investigation (SUMI) polarimeter that has been designed to measure the polarization in the ultraviolet lines of CIV and MgII which are formed in the transition region and upper chromosphere. We are currently developing this polarimeter and other optical technologies required to build an instrument that will achieve a major advance in the measurement of magnetic fields in this wavelength region. Initially configured as a sounding rocket payload, such a UV magnetograph would allow us to make exploratory measurements extending the observation of solar magnetic fields into new and dynamic regimes.

2. SCIENTIFIC RATIONALE

A primary goal of NASA's Sun-Earth Connection Program (SEC) and the Living With a Star initiative (LWS) is to develop an ability to predict when a stressed magnetic active region is about to undergo an explosive event that launches a coronal mass ejection (CME). *Yohkoh* coronal X-ray images have shown that CME explosions are more likely to occur in regions having sigmoidal coronal magnetic fields than in regions with less contorted field configurations. The degree to which the contorted fields depart from a potential configuration represents the free magnetic energy content of the region and is evidently a good indicator of whether a region will produce CMEs. This qualitative lead is being pursued. The free magnetic energy content of a region can be estimated from integrals over vector magnetograms, but accuracy depends on the fields being measured at a sufficient height in the atmosphere for them to be very nearly force free.

Also, the force-free fields in the transition region and corona may undergo large changes in direction without measurable change in the photospheric roots. So, to follow the evolution of the 3D force-free field (both for CME studies and for more general purposes), the vector magnetograms from which the field is extrapolated must be obtained from a force-free layer. Therefore, to meet the goals of SEC and LWS, measurements of the vector magnetic field in the middle to upper chromosphere and/or lower transition region are needed [4]. The ultraviolet spectrum is rich in magnetically-sensitive strong emission lines that are formed at various temperatures throughout the chromosphere, transition region and low corona. Our approach to achieve the measurements of the vector field in the low-β regions of the solar atmosphere is to develop a vector magnetograph that measures the polarization in one or more of these lines. Such an instrument would be a crucial complement to all visible-light magnetographs, on ground or in space, both in any attempt at forecasting CMEs and in the more general problem of determining the 3D structure and evolution of the coronal magnetic field.

For the desired sensitivity to the Zeeman effect, the lines should have steep wings, low adjacent continuum intensity, and a simple Zeeman pattern. To obtain accurate measurements of the magnetic field in this region, SUMI will use two pairs of lines having complementary characteristics. The first pair (MgII) is formed in a narrow region and is optically thick, thus avoiding line-of-sight superposition uncertainties. A second pair (CIV), although optically thin, is still formed in a fairly narrow range of heights and provides a particularly simple emission line profile for analysis. Lande-g factors, an indication of the magnetic splitting, for both pairs of lines are ~1.2.

The profiles of the MgII *h* and *k* lines at 2795 Å and 2803 Å show broad, deep absorption that is formed in a layer containing the upper photosphere and low chromosphere. Although the absorption components of these lines have a weak polarization due to resonant scattering[1], this polarization is not very useful because of the small slope of the absorption profile. Instead, the line core, which shows a large central emission that is reversed in the quiet Sun, but not in sunspots, can be used in magnetic field measurements[2]. The emission in this spectral range is formed in a narrow range of temperatures at the top of the chromosphere[3]. The line formation processes for these lines are similar to those for the CaII *H* and *K* lines. The main difference in the CaII lines and the MgII lines is that the CaII lines show only small emission cores and are formed lower in the solar atmosphere. The emission cores of the MgII lines have a very sharp rise and a good contrast with respect to the weak intensity at nearby wavelengths. These line cores form in a relatively small range of altitudes (~300 km in extent) near the top of the chromosphere, well separated from the levels where the optical lines are formed. For these reasons, this pair of lines is ideally suited for studies of the magnetic field at the top of the chromosphere.

In the UV, the CIV (2s-2p) lines, at 1548.2 Å and 1550.8 Å, are observed to have simple emission profiles that are formed ~200 km higher than the MgII lines and at a temperature of ~10^5 K. Although these lines are more straightforward to analyze, they lie deeper in the UV making them more difficult to observe. However, this is taken into consideration in developing the SUMI technology (Section 3).

3. SUMI SOUNDING ROCKET PROGRAM

The current focus of the SUMI program is to develop three of the optical technologies that will allow us to build a UV solar vector magnetograph to investigate the currently unmeasurable magnetic fields in the transition region and upper chromosphere. Specifically the program is aimed at developing materials and coatings to extend the operating range of standard optical components to work in the vacuum UV with the objective of making polarization images of the Sun at wavelengths of 1550 Å and 2800 Å.

In this program we are:

- Developing the UV cold mirror technology required to reduce the thermal load on a solar-observing UV magnetograph and test the durability, thermal characteristics and aging properties of the UV cold mirror coatings.
- Optimizing the polarizing optics for simultaneous observations of the MgII and CIV emission lines.
- Developing a double Wollaston UV analyzer which will allow simultaneous observations of orthogonal polarizations for each emission line.

This paper describes the progress that has been made in the development of the polarizing optics for the SUMI sounding rocket program. A separate paper[4] describes the cold mirror technology that will be used on the SUMI telescope. The ultimate goal of this program is to develop a UV/chromospheric vector magnetograph for an Explorer Mission that will complement the visible light/photospheric magnetograph observations of the Japanese Solar-B Mission and the Solar Dynamics Observatory planned under the LWS. Using these observatories in conjunction, solar scientists will finally be able to study the three dimensional, dynamic evolution of solar magnetic fields and their influence on solar activity.

3.1 BASELINE DESIGN OF SUMI TELESCOPE

The solar telescope design must solve the thermal problems associated with direct solar viewing. The standard solution has been to use a Gregorian design with a field stop between the primary and secondary mirrors. While this restricts the field of view, it reflects the unwanted light from the region outside of the aperture stop. The disadvantages of this design are a longer optical path and a larger secondary, decreasing the collecting area of the telescope. Our approach uses a Ritchey-Chretien telescope design (Figure 1) with special optical coatings, applied to the front surfaces of both the primary and secondary mirrors, that reflect only the narrow wavelength ranges that we plan to observe. This results in a "cold mirror", i.e., a "self-filtering" telescope. The rear surface of the primary mirror is figured and has a broadband coating that reflects the unwanted radiation back through the telescope. An advantage of this design is that the field of view is not restricted and the whole Sun can be imaged so that slit-jaw imaging can provide context information.

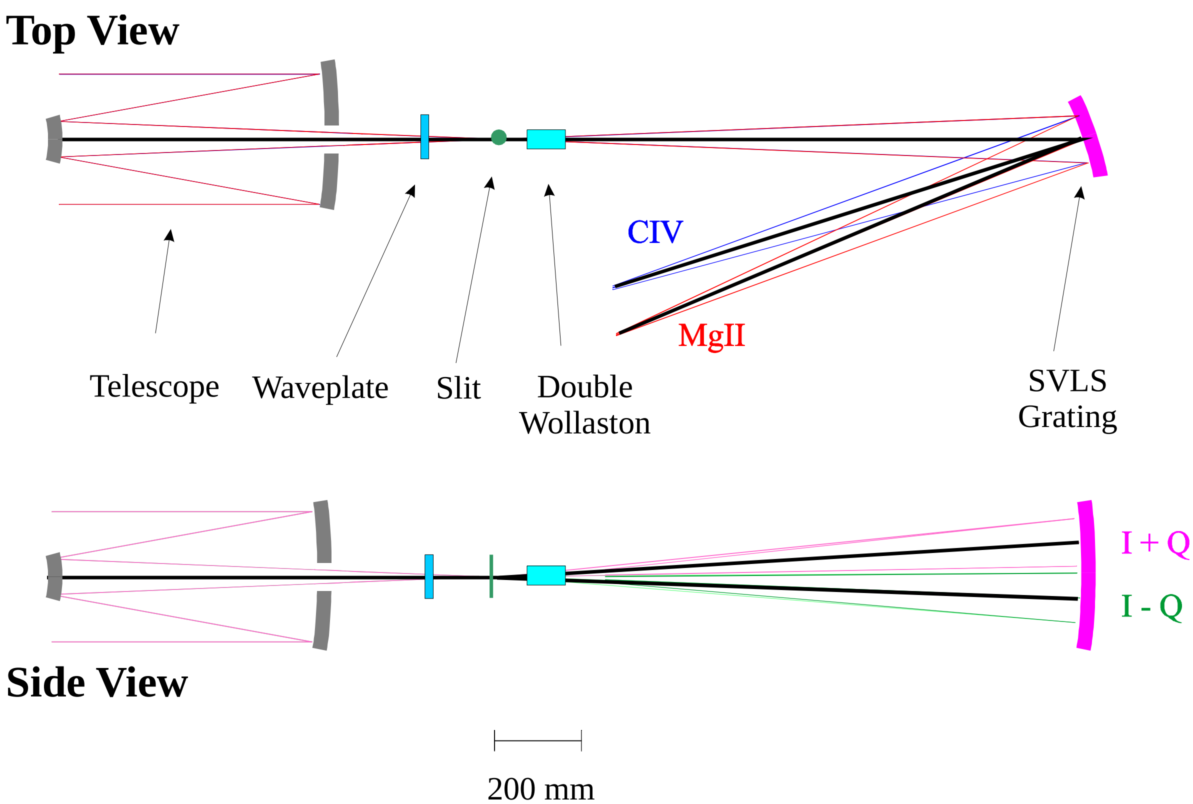

FIGURE 1. SUMI telescope design. The top view shows the wavelength splitting of the grating while the bottom view shows the two output beams of the double Wollaston analyzer.

In order to observe the Stokes profiles, a spectrograph is required to provide the necessary wavelength resolution for the Stokes polarization analysis. Given a fixed overall instrument length, a Ritchey-Chretien design allows the length of the spectrograph arm to be increased; thus improving the wavelength resolution.

The SUMI telescope mirrors have dielectric coatings which maximize the CIV and MgII reflectivity. The coating design is simplified by the fact that we are interested only in narrow spectral ranges. Along with improving the thermal environment, these narrowband UV reflection coatings reduce the infrared and visible light ($\times$ ~0.002) incident on the SVLS grating; simplifying the spectrograph design.

3.2 SUMI WAVEPLATES

A sounding rocket program places serious time constraints on any observing program. The limited observing time and the weak linear polarization signals expected in this wavelength region in all but the strongest magnetic fields require us to optimize the polarimeter for the strongest source, circular polarization (V). While circular polarization will be the primary measurement, exploratory measurements of linear polarization (Q) will be made in the MgII line. The proposed modulation scheme is shown in Table 1.

Table 1. Modulation scheme of SUMI sounding rocket polarimeter. Conventional (reflective) analyzers measure one polarization at a time. With a double Wollaston, the polarization that is normally discarded is measured by the 2nd channel of the analyzer.

Waveplate Fast Axis	Measured polarization (Double Wollaston)	
(degrees)	Channel 1	Channel 2
45, 225	I+V	I-V
135, 315	I-V	I+V
0, 90, 180, 270	I+Q	I-Q

I = Intensity

Q = linear polarization at 0° to Channel 1

U = linear at 45° to Channel 1 (*not measured*)

V = circular polarization

Figure 2 shows the retardation characteristics of three waveplate designs that are being pursued in our UV magnetograph development program. In these designs the optimum retardance is +/-90° at CIV (and MgII) With this retardance, the sensitivity to the Q (linear) and V (circular) polarization is the same for a given measurement. Using only a single waveplate, this polarimeter design will not measure the U linear polarization but maximize the polarization efficiency of the Q and V measurements for a given detector signal to noise (S/N). In order to achieve a quarterwave (90°) retardance using only MgF_2, a 1st order waveplate design (retardance = 630° = 4π – π/2) was optimized for CIV. The retardance at MgII is approximately 300°. The resulting loss in polarization sensitivity is offset by the larger MgII flux levels ($10^3 \times$ CIV flux). Two achromatic waveplate designs are also being developed. One design uses MgF_2/sapphire, the second MgF_2/UV quartz. Both of these designs have the same retardance (90°) at CIV and MgII. The MgF_2/sapphire design has an advantage over the MgF_2/UV quartz and the MgF_2-only designs since it has a larger field of view. This is due to the fact that the negative birefringence of the sapphire cancels the positive birefringence of the MgF_2. The main concern for these achromatic designs is the total optical thickness, which will reduce the transmission at CIV.

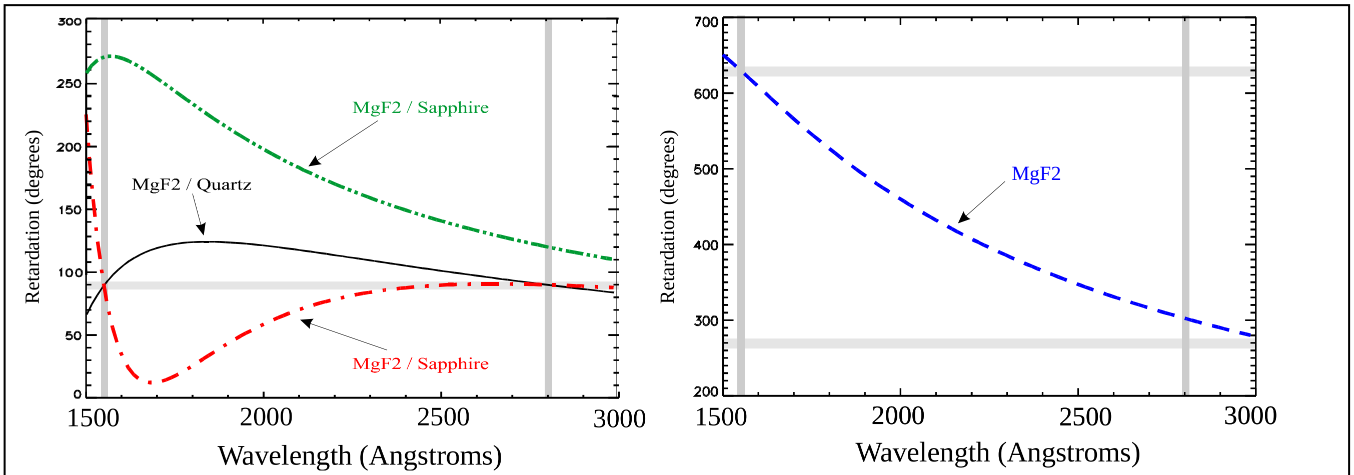

FIGURE 2. Retardation characteristics of SUMI waveplates

3.3 SUMI ANALYZERS

In a previous UV spectro-polarimeter[5], a grating was used to analyze the polarized light from the Sun. Because of large wavelength variations in the polarization properties of the grating, a four-mirror analyzer was inserted at those wavelengths where the resolution of the grating was low. Unfortunately the four mirror-analyzer had very low transmission properties (~5%.). SUMI is pursuing two different analyzer designs: (1) a two mirror reflective analyzer or (2) a double Wollaston beamsplitting analyzer (Figure 3). If a two-mirror analyzer is selected, it will be aligned to maximize the transmission and polarization resolution through the spectrograph grating . While the two mirror analyzer has a simpler optical interface, the double Wollaston can achieve a higher polarization resolution over a large wavelength range and it has a higher total throughput than "typical" UV reflective analyzers. Also, the double Wollaston can make simultaneous measurements of orthogonal polarizations (i.e. I±V). These simultaneous measurements can reduce the intensity (*I*) crosstalk in the circular polarization measurement (*V*) created by source variations. This is especially important for UV lines formed in the upper chromosphere and transition region where changes in emission line intensity are known to be quite rapid even during non-flaring periods[6]. This crosstalk reduction is necessary if we are to detect the rapid changes in the polarization of these lines that can be expected, if, as generally believed, the origin of the rapid magnetic changes that trigger flares and other activity is in these regions.

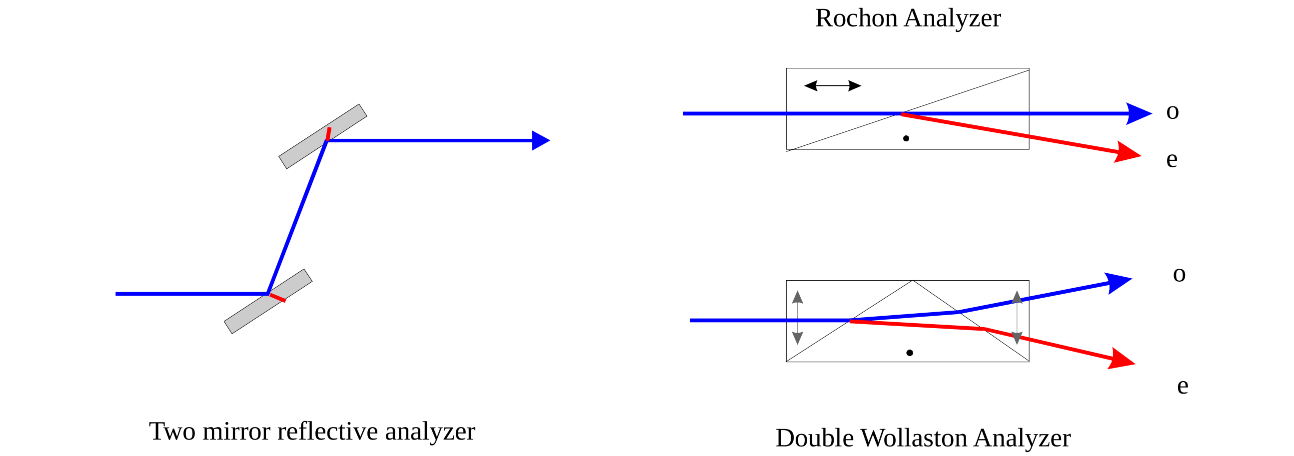

Figure 3. Analyzers that are being developed for the SUMI technology development program. The Rochon polarizer is used in the calibration of SUMI optics (o-ray only). The double Wollaston (the primary candidate for SUMI) has twice the beam separation of the Rochon, thus doubling SUMI's field of view. The two mirror reflective analyzer has the simplest interface for the spectrograph. The arrows on the Rochon and Wollaston polarizers represent of the optic axis of the MgF_2 crystals.

4. SUMI OPTICAL TEST PROGRAM

This section will describe the polarization test program that is being performed at the Marshall Space Flight Center UV test facility. Section 4.1 will describe the test facility and the instrumental errors that must be corrected in the test programs for SUMI polarimeter. Section 4.2 will describe the test setup and polarization measurements of the SUMI double Wollaston analyzer.

4.1 SUMI test facility

A vacuum UV spectrophotometric test facility (Figure 4) has been developed at the NSSTC/MSFC for measuring the optical properties (transmittance, reflectance and polarization) of test samples in the wavelength range from 1150 Å through the visible. This facility was used to test the Ultraviolet Imager for the International Solar Terrestrial Physics Mission and for the Wide Imaging Camera for the IMAGE Mission. For VUV optics, contamination is a serious concern. In order to minimize exposure of test optics to contamination, the spectrophotometric system is contained in a stainless steel vacuum chamber maintained in a class 1000 clean area. A cryogenic hydrocarbon-free pumping system is used to avoid contamination. The vacuum system operates with a base pressure in the 10^{-7} torr range. For VUV measurements, a high-pressure arc discharge deuterium lamp is used as the source. Because of its continuum output in the 1150-3700Å range, this source is used to scan the transmission, reflection and polarization characteristics of the SUMI optics in the CIV and MgII wavelength bands. A 0.2m vacuum monochromator, with a concave holographic grating (1200 lines/mm) coupled to a 76.2cm focal length collimating UV enhanced mirror system, produces a 10.2cm monochromatic collimated incident beam. Two vacuum compatible linear stages and two rotational stages are used to position the detectors, optical components and test samples during the calibration and testing process.

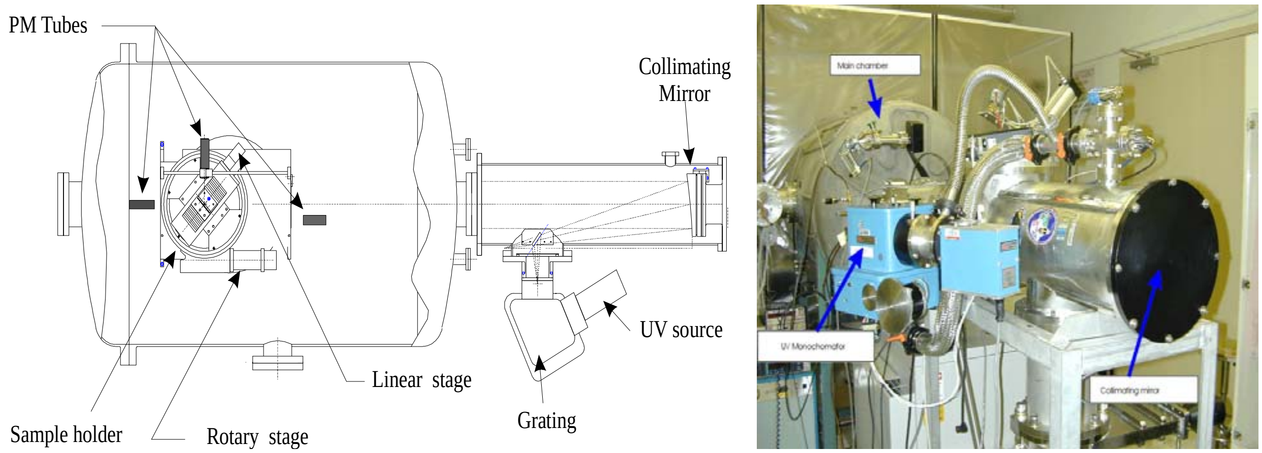

FIGURE 4. MSFC VUV TEST CHAMBER

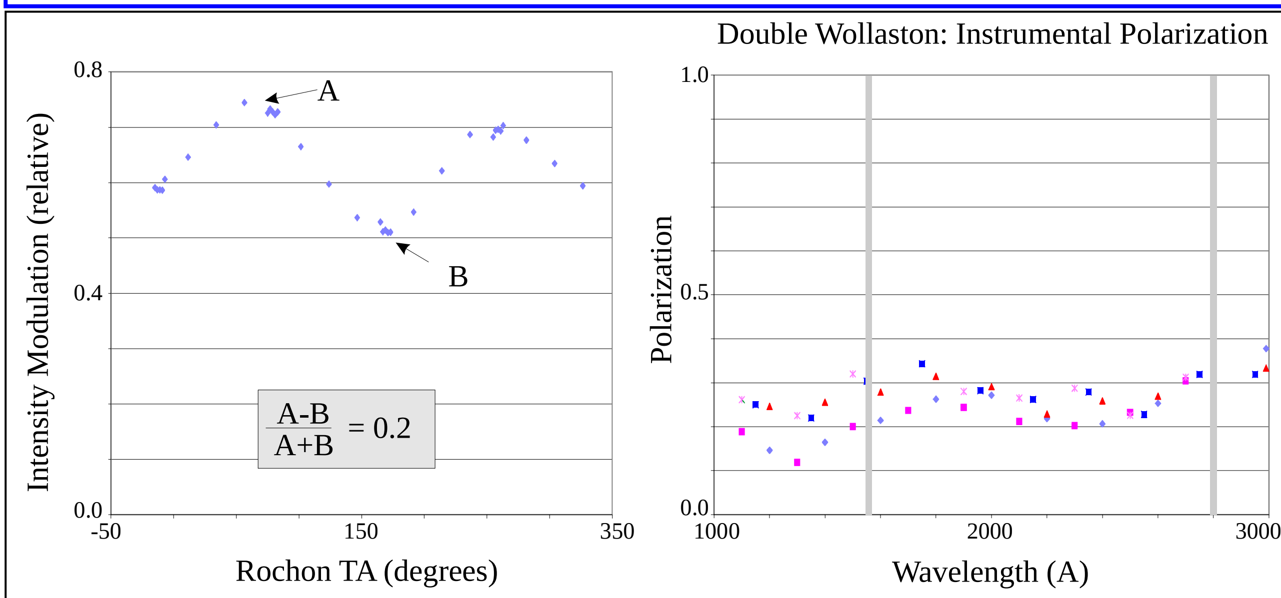

FIGURE 5. INSTRUMENTAL POLARIZATION

For the transmission and reflection tests, the instrumental polarization from the grating and fold mirrors can be normalized by monitoring the source. In order to measure the extinction ratio of the SUMI polarizers (double Wollaston and reflective) and the SUMI waveplate retardance, a UV Rochon polarizer is inserted between the grating/fold mirrors and the test samples to introduce a known polarization. Figure 5 shows the effects of instrumental polarization observed during the “total”

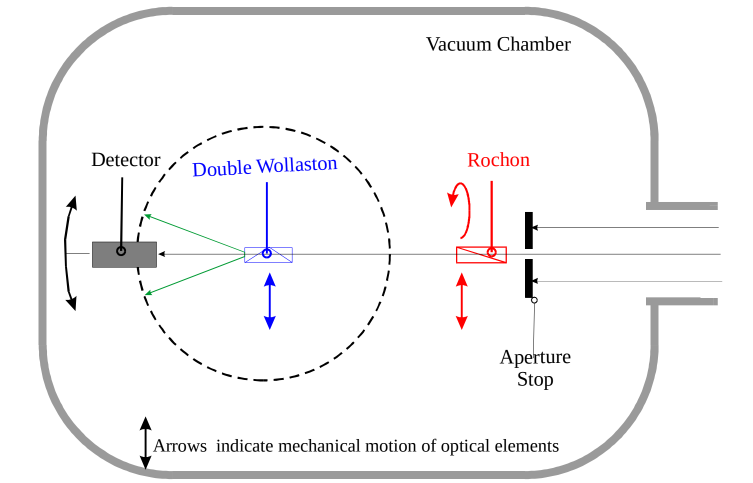

FIGURE 6. TEST SETUP OF DOUBLE WOLLASTON SHOWING ROCHON, AND DETECTOR POSITIONS

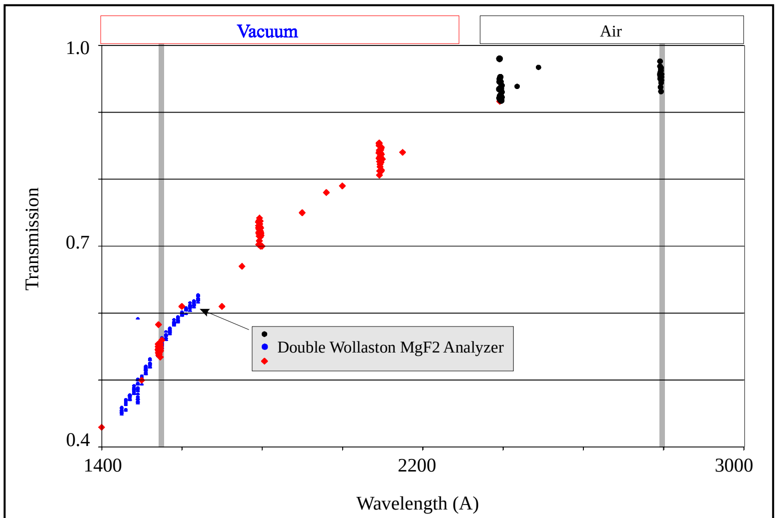

FIGURE 7. DOUBLE WOLLASTON: TRANSMISSION MEASUREMENTS

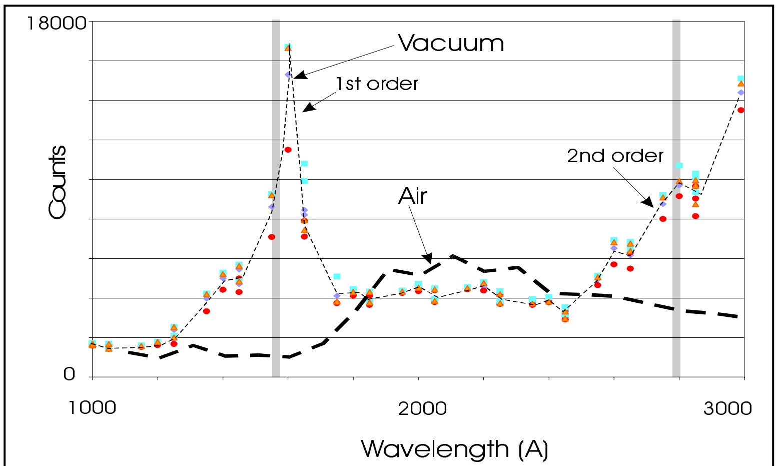

FIGURE 8. DEUTERIUM SOURCE IN AIR AND VACUUM

transmission tests of the Rochon and Wollaston polarizers. In the left panel the double Wollaston is removed from the beam and the intensity of the on-axis beam (Figure 3, o ray) from the Rochon is measured as a function of the transmission axis (TA) position. In the right panel the Rochon is removed and the difference between the two beams exiting the double Wollaston is plotted as a function of wavelength. In both cases the instrumental polarization is above 20%. The next section will describe the test setup and polarization measurements that were made on a double Wollaston analyzer.

4.2 Double Wollaston analyzer

Figure 6 shows the test setup for the double Wollaston tests. A Rochon polarizer is mounted on a small rotary stage which allows the transmission axis to be rotated a full 360 degrees. A UV-sensitive PM tube is mounted on a large rotary stage and the double Wollaston mounted to a linear stage that is placed at the center of the detector rotary stage. The linear stage allows the double Wollaston to be removed from the optical path so that the detector can measure the signal from the Rochon as a function of wavelength and transmission axis position. The Wollaston analyzer is then inserted into the optical path and the detector is rotated +/- 10 degrees to find the maximum intensity of the two beams exiting the double Wollaston polarizer.

Figure 7 shows the total transmission of the double Wollaston relative to the source intensity from the Rochon when the Wollaston is removed. Since the "total" transmission is greater than 50% over most of the wavelength range, the double Wollaston (and Rochon) polarizer are more efficient than reflective analyzers which can never have a transmission greater than 50%. One instrumental error that must be eliminated when testing over this wavelength range is the monochromator wavelength crosstalk. In the vacuum tests there is a gradual increase in the transmission from 45% at 1400 Å to ~85% at 2400 Å. Above 2400 Å the vacuum measurements would show a sudden drop in the measured transmission. This drop is instrumental and is related to the detector seeing both the 1st order and 2nd order wavelengths (Figure 8) in the source measurements when the Wollaston is removed. Therefore, the first order wavelengths (1200 Å - 1600 Å) contaminate the second order measurements (2400 Å – 3200 Å). Although this problem can be reduced when the chamber is backfilled with nitrogen, oxygen must be allowed into the chamber to completely eliminate this wavelength crosstalk in the source measurements.

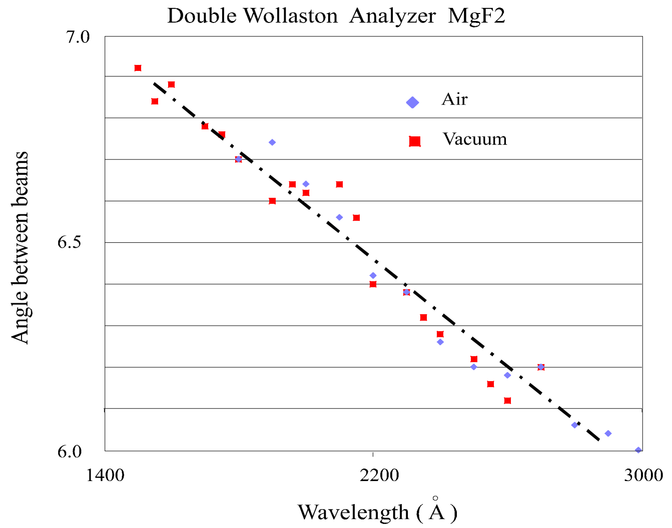

FIGURE 9. DOUBLE WOLLASTON: BEAM SEPARATION VS WAVELENGTH

Since the beam separation of the double Wollaston is wavelength dependent, this was also measured and is shown in Figure 9. Because of this beam separation the large SVLS grating in Figure 1 will actually be two gratings so that each optical path (I+Q and I-Q) can be optimized.

Although the birefringent analyzers, the double Wollaston and the Rochon, have good polarization and transmission properties at the principal wavelengths that SUMI will observe, birefringent polarizers have optical aberrations that must be understood and minimized. Since the SUMI sounding rocket program has a limited observing time, two cameras will be used for each wavelength band which will minimize the chromatic aberrations. The field of view is limited to 4.5 arc minutes in order to minimize the spatial crosstalk of the beams exiting the polarizer (I+Q,I-Q beams in Figure 1). This limited field of view and the slow beam from the telescope (a 3.7 meter effective focal length and a F/# = 12.4) minimize the coma and spherical aberrations that are expected in this polarimeter design. Figure 10 shows the diffraction pattern from a slit placed in front of the double Wollaston analyzer. A detector has been placed after the double Wollaston and a calibration polarizer is rotated to three positions: 0, 45 and 90 degrees. In order to separate the two beams on the detector only 2 millimeters of the slit was illuminated with a HeNe laser. The top image shows the slit with the double Wollaston removed; the next three panels show the output from the Wollaston for the three positions of the calibration polarizer.

5. SUMMARY

Measurement of the magnetic field in the transition region and upper chromosphere is crucial to understanding the dynamic events that occur in the outer layers of the solar atmosphere. Most of the Zeeman-sensitive lines in this region of the solar atmosphere occur in the ultraviolet. The CIV line at 1550 Å and the MgII line at 2800 Å have been selected for the SUMI baseline design. Of the two, the CIV line is pushing the technology, since (1) the irradiance of the solar spectrum is approximately three orders of magnitude smaller in its spectral range than in the range of MgII, and (2) most birefringent crystals (sapphire and UV quartz waveplates) that work in the UV start absorbing at wavelengths below 2000 Å. Some of the polarization optics that are being developed in the SUMI technology program may be useful only in an orbital mission that have long observing times. Their use in a sounding rocket program will be contingent upon the observing program and the radiometry of the instrument package. Because of the high transmission and polarization efficiency, the double Wollaston is the leading candidate for the SUMI sounding rocket program. Its actual use will be dependent upon the spectrograph design and the mechanical interface requirements of the sounding rocket which is currently being studied.

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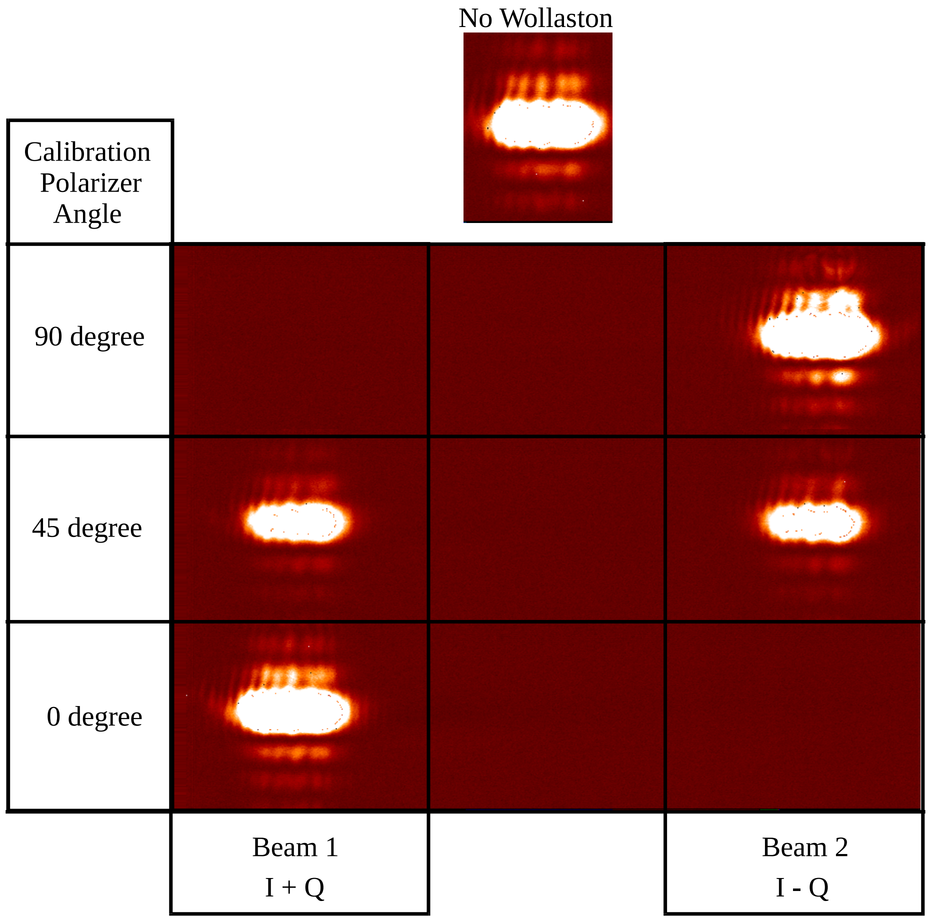

FIGURE 10. DOUBLE WOLLASTON: OPTICAL CHARACTERISTICS / SLIT IMAGES

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